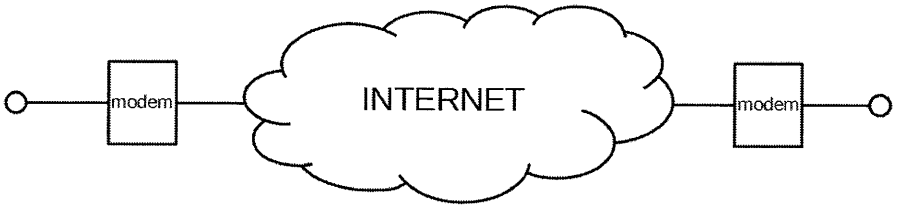
Bandwidth, bitrate, 2B1Q- 5/10

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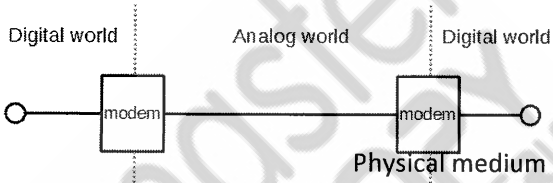
What do we find at physical layer of a communication system?



We have a physical medium which connects two points of the network, but also is in between two digital worlds, hence a translation is needed.
The latter is implemented by **modems**: mod*ulator*/dem*odulator*

- Modulator: translates from digital to analog
- Demodulator: translates from analog to digital

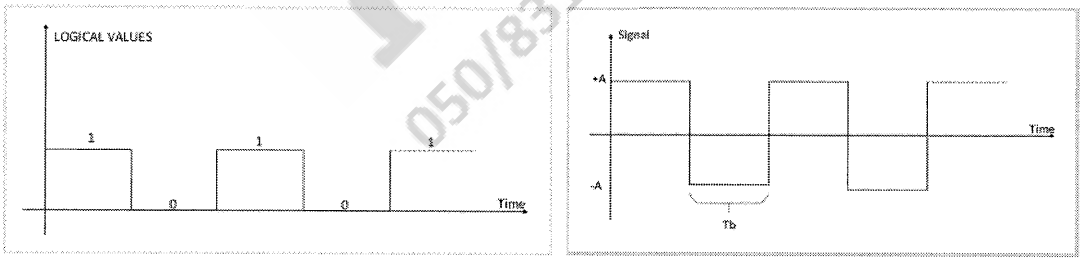
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The fundamental quantity for a network and for links in general, is called **BIT RATE** (R_b), measured in bit per second.

Bandwidth

An information to transmit can be represented with a stream of logical values, bits, within the digital world.
Since a translation is needed, a **MAP** is needed, *in order to translate* those logic values into physical ones, usually voltage or current signal with a certain amplitude A.



T_b is a certain amount of time needed to transmit 1 bit.
An operational meaning of bit rate is *"How many bits can fit within 1 second of time"*.
If, for example, $T_b = 1s$, hence $R_b = \frac{1}{T_b} = 1\ bps$

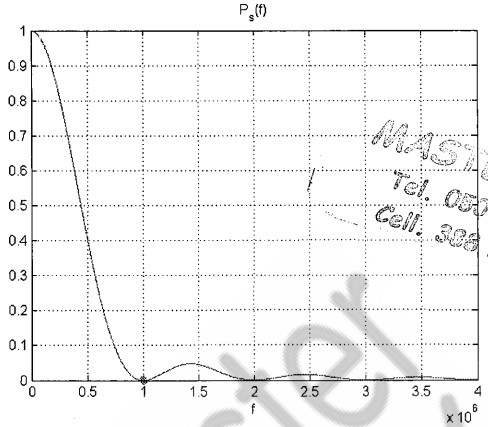
Since a signal can be represented within the frequency domain, and since also minister releases slices of 4MHz of bandwidth to transmit, we must be sure that our signal does not invade other slices assigned to other signals.
The shape of the signal in the frequency domain is related to the shape of the signal which represents a single bit in time domain.
In the example above we used a way to represent bit stream which is called NO-RETURN-ZERO (NRZ).
For a such represented signal, can be proved that its power spectrum density has the shape

described by the *sinc* function

$$sinc^2(x) = \left(\frac{\sin(x)}{x}\right)^2$$

More precisely we talk about the **power spectrum density**, that is how power is distributed all over the frequencies and this justifies the presence of the square.

$$P_s(f) = \left(\frac{sin(fT_b)}{fT_b}\right)^2 = sinc^2(fT_b)$$



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We represent only half of the spectrum cause the other part is symmetric with respect to the first. Note that this is true only for real signals (Hermitian symmetry).
Since $f \in [0, +\infty]$, we may note the presence of the spectrum within the same range. In practical cases, instead, the most part of the spetrum density is located between zero and the first point where spectrum reaches 0 as amplitude *(First null)*.
Hence the **bandwidth** of our signal is the following **interval of frequencies** $B = \left[0, \frac{1}{T_b}\right]$.

We can observe that $B = \frac{1}{T_b} = R_b$. Cases like this are misleading: while numerically equal, bitrate and bandwidth are two different concepts and should be kept separated.
In fact this equality only happens in this case with this wave-form. With other waveforms, the bandwidth is different from the bitrate.

Multilevel Signal

There are cases in which we realize a different and smarter type of **MAPPING**. One of these is called **2 bits 1 quaternary** (2B1Q), where we have a physical signal with 4 possible different amplitudes. Hence we associate at each level a pair of bits.
2B1Q was used by ISDN: *Integrate Service Digital Network*.
This was the first kind of integrate telephony and computer communication architecture. It was so futuristic to be a failure due to costs.

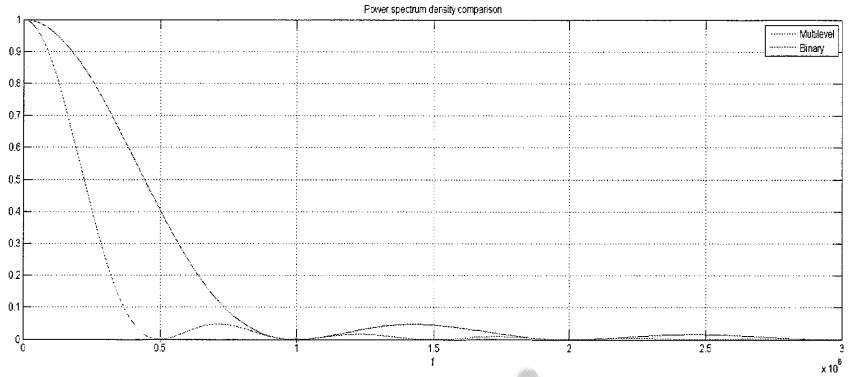
When I transmit "3A", I'm transmitting the information stored in bit "01" in one time!
T_s is the time of each pulse, aslo called **Symbol time**.
Since each bit is available to transmit after a certain time, T_b, and we have 2 bits within the same symbol, hence
The symbol time is:

$$T_s = 2T_b \rightarrow R_s = \frac{1}{T_s} = \frac{1}{2T_b} = \frac{R_b}{2}$$

R_s is known as **symbol rate** and it is the rate at whch i see pulse at the physical layer, measured in symbol per second or in **Baud per second**

$$1\,Bps = 1\frac{Symbol}{s}$$

What is the purpose of this application?
If i have a $T_b = 1\mu s \rightarrow R_b = 1Mbps$. If instead of bits directly mapped i transmit symbols, i have $T_s = 2T_b = 2\mu s \rightarrow R_s = 500kHz$
Since the shape of the symbol is still rectangular, we will have the same shape of power spectrum density, but since the signal in time is slower, the first null band will be smaller as well.
Hence, **bandwidth reduced!**



More precisely I have reduced the rate at which symbols arrives at destination, since $T_s = 2T_b$, but the amount of information is still the same, cause within a single symbol we have stored 2 bits.
Hence, i transmit the same amount of information with a reduced amount of bandwidth.
This leads to two important conclusions:

1) I can transmit using the same "speed" in terms of R_b but with a reduce amount of bandwidth
2) I can transmit using the same amount of bandwidth but with an increased speed in terms of R_b

In general if we have M different levels of physical signal:

- The number of bits stored within one symbol is $N_b = \log_2 M$
- The symbol time is $T_S = N_b T_b$

Hence:

$$R_s = \frac{R_b}{N_b} \qquad T_s = \log_2 M \cdot T_b \rightarrow \eta = \frac{T_s}{T_b} = \log_2 M \ \ spectral\ efficiency$$

Finally, the bandwidth of a signal (in Hz) is equal to the symbol rate (in Baud)

$$B = R_S$$

Putting all together we get:

$$R_s = \frac{R_b}{N_b} \rightarrow R_b = \log_2 M \cdot R_s$$

Note: $\forall\, M > 2,\ R_b > R_s$

If $M = 2$ we are talking about a binary signal with only two possible amplitudes, hence $T_s = T_b \rightarrow R_s = R_b$
If instead $M > 2$, we always have the described advantages.

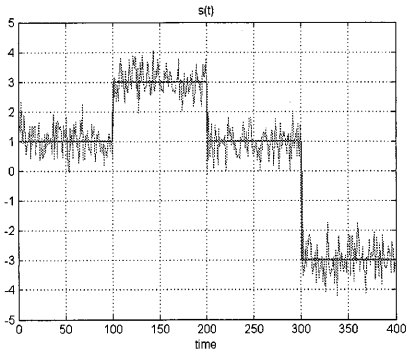
Example:

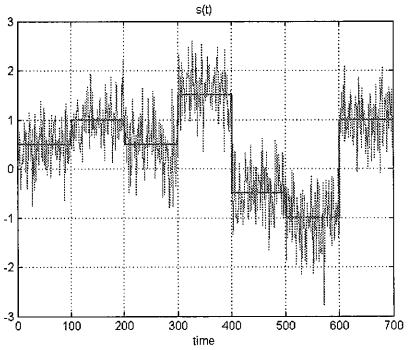
In ADSL we have a bandwidth of 1MHz (at baseband) and a bit rate of 10Mbps, hence how many level do we have?
$B = 1MHz, R_b = 10Mbps \rightarrow$

$$R_b = \log_2 M \cdot R_s = \log_2 M \cdot B \rightarrow \log_2 M = \frac{R_b}{B} = 10 \rightarrow M = 2^{10} = 1024$$

And what about increasing M?
The total power spent to transmit is directly related to the maximum amplitude of physical signal. Hence, to not spend too much, we fix the maximum amplitude to a certain value. If we increase the number of levels for a fixed amplitude, all levels will come closer each other and a small amount of noise or interference is sufficient to corrupt symbol. (corrupt -> make a certain symbol interpreted as another one)

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RF mod, BPSK, QPSK - 7/10

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Evolution of wireless communications

- 1G
  - Analog communications, no data connection, no internet
- 2G (GSM)
  - Introduction of digital binary communications (1 bit per symbol)
  - Connection oriented
- 2.5G (GPRS)
  - Bridge to next generation
- 3G (UMTS)
  - Digital quaternary communications (2 bits per symbol)
  - Packet oriented
  - Good for mails but not yet for Skype
- 3.5G (HSxPA)
  - HSUPA: High Speed Up-Link Packet Access
  - HSDPA: High Speed Down-Link Packet Access
  - 16 QAM -> 4 bits per symbol
- 4G (LTE)
  - 64 QAM -> 6 bits per symbol
- 5G
  - 10 bits per symbol
  - Current field of research

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Radio Transmission

In radio transmissions, we have two fundamentals quantities:

1) Frequency (f) Hz
2) Wavelength (λ) m

Related by the following equation:

$$\lambda = \frac{c}{f}$$

Where c is the speed of light $c \approx 3 \cdot 10^8\ m/s$

The information represented in bits is converted into a physical signal which now must be translated again into a radio one, hence i need a sort of converter from electric current to radio waves and the latter is the antenna.

In order to make radio transmission working properly, the size of the transmitting antenna must be comparable to the size of the receiving one (at least same order of magnitude).

If for example we have 1MHz of bandwidth and 1Mbps of bit rate, we have a wavelength

$$\lambda = \frac{3 \cdot 10^8}{10^6} = 300m$$

Hence we should have a 300 m antenna, which is impossible for applications as smartphones.

To reduce the dimensions of antenna, we need to work at **higher frequencies**, in order to increase f and obtain smaller value of λ.

Analog modulation

Just to put some numbers: a smartphone has the size of an hand, around 20 cm, hence we should work at: